Enhancement of Pacific Threadfin *Polydactylus sexfilis* in Hawaii: Interactions Between Aquaculture and Fisheries

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Abstract

Many coastal fisheries in the Hawaiian Islands show evidence of depletion through over fishing or loss of critical habitat. While conventional stock management (imposition of harvest controls) may aid some over fished stocks to recovery, generally such recovery is slow and subject to variability of natural recruitment. Research into the feasibility of stock enhancement (release of hatchery-reared fish to supplement stocks and reproductive success) in Hawaii on Pacific threadfin (moi, *Polydactylus sexfilis*) has established the information necessary to design and implement a responsible enhancement program, and has demonstrated the potential contribution released fish can have on localized fisheries. Current research is examining threadfin behavior and conditioning, fisheries demographics and ecology, genetics, the ecological basis of recruitment success and means to determine the contribution of hatchery-reared fish to reproduction and stock recovery.

Introduction

In Hawaii, as in other locations around the world, local fishery yields have leveled off or are decreasing (Shomura, 1987). Many stocks are over exploited, fully exploited or of questionable status. While the state Division of Aquatic Resources, the responsible management agency, collects catch data for holders of commercial fishing licenses, most of these fishers target offshore pelagic or demersal fisheries. The state does not license recreational or subsistence fishers, nor does it collect catch data from shoreline fishers who target coastal and inshore fisheries.

Resource managers have a range of options for managing depleted fisheries stocks. For growth-limited fisheries, where fishery yield is less than maximum sustainable yield due to over fishing, managers typically enact regulations to restrict fishing effort, either through catch limits, size limits, gear restrictions, closed seasons or some combination. Recently, managers are examining the effectiveness of establishing natural reserves, or implementing community-based management for localized fisheries.

Recruitment-limited fisheries are those whose rate of natural reproduction and/or recruitment is less than that needed to maintain the population at optimal levels. The limit to reproduction is primarily due to severely depleted adult (reproductive) stocks, loss of spawning or nursery habitat, or both. In such cases, even complete bans on the taking of these stocks may not result in recovery, or recovery may be extremely slow because the net rate of increase of the population is low, or inter-annual variations in recruitment result in only sporadic strong year

classes. For recruitment-limited stocks, management options include increasing recruitment through propagation and release, most commonly of competent juveniles, but potentially of mature adults as well, or restoring degraded spawning and nursery habitat.

Coastal fisheries in Hawaii are sensitive to natural variations in environmental conditions, particularly rainfall and runoff and high surf events, as well as man-made environmental perturbations such as coastal dredging and sedimentation from terrestrial sources. The impacts of these perturbations most strongly influence early survival, and are one of the primary factors affecting inter-annual variations in recruitment success.

The Pacific threadfin, *Polydactylus sexfilis*, is one of the most culturally important, locally popular coastal fish species in Hawaii. *P. sexfilis* is a member of family Polynemidae, comprising 33 species with tropical and subtropical distributions. Pacific threadfin in Hawaii is known as moi, the "fish of kings."

Pacific threadfin is an ideal candidate for a stock enhancement program. The Pacific threadfin fishery in Hawaii is highly depleted, and in response, there are regulations setting limits on the daily catch, minimum size, and a closed season. All available evidence suggests Pacific threadfin is recruitment limited, at least on the island of Oahu. Culture techniques for the species are well established. The fish spawn spontaneously in captivity, produce large numbers of healthy fry, and can be grown to a size appropriate for tagging within 60-90 days after hatch. The juveniles inhabit defined nursery habitats, high wave energy sandy beaches, while the adults move offshore to sand patches in hard bottom areas.

The Oceanic Institute has been conducting research into the enhancement of depleted fisheries for over a decade, currently focusing on Pacific threadfin, an important but depleted coastal fishery in Hawaii. Our capability at the Institute to produce large numbers (100,000 per month) of healthy fry on a continuous basis, combined with Hawaii's advantages of year-round warm temperatures, unpolluted coastal waters and undegraded habitats, form the foundation for innovative enhancement research.

Early research on Pacific threadfin focused on the determination of optimal release strategies (size, site and season) (Leber *et al.*, 1998). Having established a capability to produce, tag and release large numbers of fry with reasonable return rates, the focus of our enhancement research has turned from "can we release and recapture fish" to "how do we conduct enhancement responsibly?"

Research Components

Eight primary areas of research for Pacific threadfin stock enhancement development have been identified for focus by the Hawaii Stock Management (HSM) Program at the Oceanic Institute.

These are culture technology; release optimization; fisheries demographics, ecological interactions and habitat utilization; behavior and conditioning; health management; genetic management; economic considerations; and the ecological basis of fishery production. All research has been conducted along the windward coast of the island of Oahu (Fig.1).

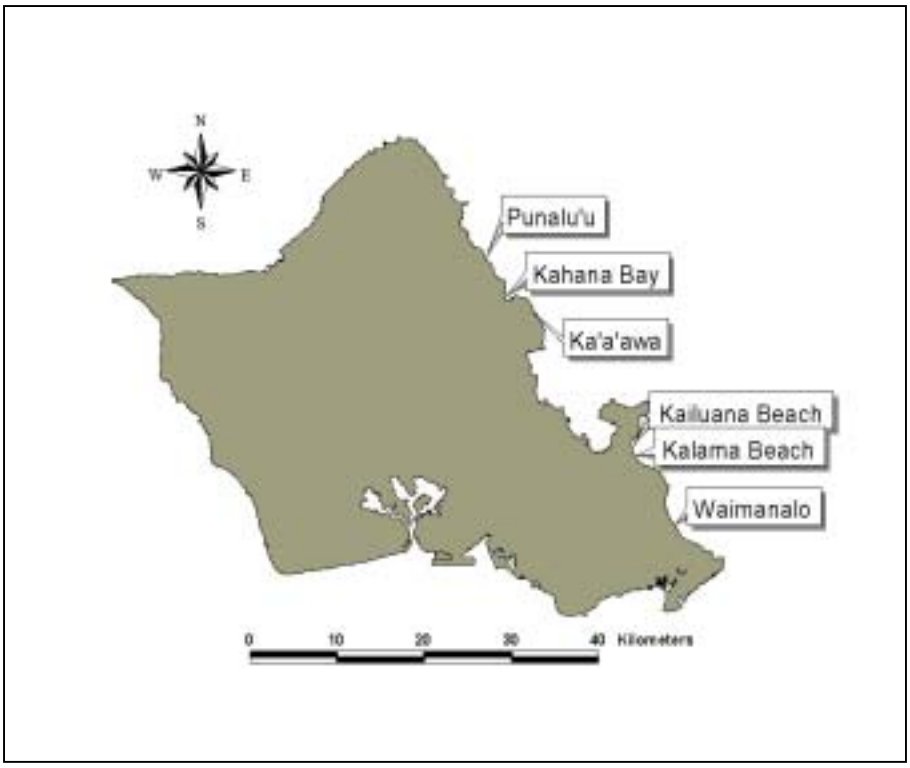

Figure 1. Map of Oahu, Hawaii, showing locations of primary sampling sites.

Culture and Tagging Technology

The culture of moi at the Oceanic Institute (OI) is described by Ostrowski *et al.* (1996). In brief, production runs began with the spawning of wild broodstock maintained at OI. OI maintains a large (~100) population of wild-caught broodstock, from the general areas in which release experiments are conducted. Larval rearing requires 25-30 days, depending on temperature. Larvae receive formulated and live food (rotifers, *Artemia* nauplii); juveniles receive Moore-Clark pellet feed. Survival rates are approximately 30% during the larval period, 70-80% during stage-1 nursery, and >90% after Day 40. Most fish are released into coastal waters between Day 60 for small juveniles (70-85 mm, fork length) and Day 90 for larger juveniles (130-150 mm).

Before release, all fish receive coded wire tags (cwt, Northwest Marine Technologies) in the snout area to identify a release batch of the same size fish, date and location. To determine tag retention rates, approximately 5% of each release lot are retained and examined monthly for one to six months, until the tag loss rate stabilizes (i.e., when the number lost had not increased since the previous month). Tag retention rates vary from 92.3% to 99.2%.

Release Optimization

The HSM Program conducted a multi-year study to examine the recapture rates of hatchery-reared moi released into Kahana Bay, Oahu from 1996-1999, focusing on the influence size at release had on recapture success (Ziemann *et al.*, in prep). Release experimental design was based on patterns of natural recruitment. Releases were

conducted primarily in fall and winter, the peak season for wild recruitment to the sandy beach nursery habitats. Releases and recapture sampling focused on the sandy beach habitat, which is known to be the preferred nursery habitat. Fish were sorted into four size classes and coded-wire tagged for size, location, season and replicate batch. Release size classes ranged from 70 mm, the minimum size to safely handle and tag fingerlings, to 130 mm.

Two types of recapture methods were used: beach seining and recovery of fish from commercial and recreational fishermen through the use of a creel survey and reward program. Results varied from year to year, but some trends were evident. Because the release experiments patterned releases after known patterns of natural recruitment, and thus eliminated extremes of size, out of season releases, or releases into unsuitable habitat, no major effects of size, site or season were observed. One statistically significant difference was distinguished between beach seine recapture percentages for two size classes in the 1997 releases, in which 85-100 mm FL moi were recaptured at about twice the rate of 100-115 mm FL moi. In 1997, the release period extended for two seasons of the year, allowing for a within-year comparison of summer and fall releases. For that year, smaller fish appeared to survive better than larger fish in both summer and fall, but recapture rates were slightly higher for summer releases than for fall releases. Based on these results and similar ones from a release in 1994, an optimal release strategy for Kahana Bay may be either to release small fish in the summer months or large fish in the winter.

Fisheries Demographics and Ecology

Contribution to the Recreational Fishery – The HSM Program conducted a multi-year study to examine the contribution of hatchery-reared fish to the recreational fishery along the windward coast of Oahu, Hawaii (Friedlander and Ziemann, 2003). Over 340,000 fingerlings of various sizes were implanted with coded wire tags and released in nursery habitats along the windward coast of Oahu between 1993 and 1997. Because few Pacific threadfin were present in creel surveys conducted between 1994 and 1998, Oahu fishermen were offered a $10 reward for each threadfin (hatchery-reared and wild) caught. A total of 1,882 Pacific threadfin were recovered from the reward program between March 1998 and May 1999, including 163 hatchery-reared fish, an overall contribution of 8.7% to the fishery. Hatchery-reared fish were as high as 71% of returns in the release areas. Hatchery-reared fish were recovered on average 11.5 km (SD=9.8 km) from the release site, though some had moved as far away as 42 km. Average age for recovered hatchery-reared fish was 495 days with the oldest being 1,021 days.

Cultured Pacific threadfin juveniles survived and recruited successfully to the recreational fishery, accounting for 10% of fishermen's catches on the windward side of Oahu. Recruitment to the fishery was highest for the 1997 release year; few juveniles from earlier releases were observed. Presence of a few large, fully-developed females in the recreational fishery suggests hatchery-reared fish can survive, grow and reproductively contribute to the population.

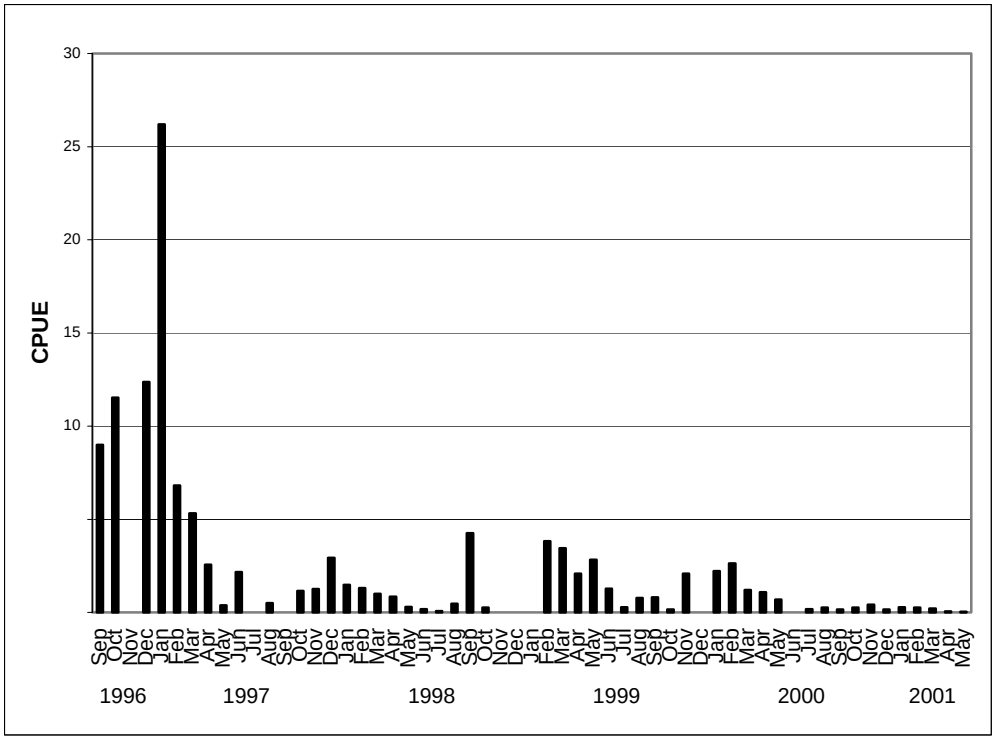

Figure 2. Mean monthly catch per unit effort (CPUE) for year 0 Pacific threadfin in nursery habitat on the windward coast of Oahu.

Monitoring Natural Recruitment The HSM Program conducted monthly beach seine surveys continuously over a five-year period (1997-2001) at six nursery habitat beaches along the windward coast of the island of Oahu (Ziemann, in prep). The beach seine measured 24 x 1.8 m with 1.3 cm mesh. During each sampling period, a consistent level of effort was followed.

Sampling efforts consisted of a series of 6 to 12 seine hauls, depending on the length of sandy beach available; data were standardized to catch per unit effort (CPUE=number of fish caught per haul). Hauls were started at a distance of about 10 m offshore or in a water depth of about 1-1.5 m and pulled directly towards shore. Sampling generally occurred during mid-tidal heights in morning but without specific regard to tidal height, times of day, or weather condition. Sampling was only conducted when surf height along the shoreline was 0.6 m or less.

The CPUE for wild threadfin juveniles collected during the recruitment study is presented in Fig. 2. Several patterns are evident. First, for all years, peak recruitment was observed during winter months (November - January), with low or no recruitment observed during summer months. Second, the inter-annual variability in overall recruitment was large, with highest monthly levels observed in 1997, and lowest levels observed in 2001. Finally, the extremely low levels observed in 2001 suggest that the particular combination of low adult population size and apparently poor larval survival resulted in almost total failure of the 2001 recruitment year class.

Habitat Utilization - Movement patterns and habitat utilization of moi (*Polydactylus sexfilis*) were assessed using data from tag-and-release studies and acoustic tracking (Friedlander and Ziemann, in press). The locations and dates of capture for each fish returned in the recreational fishery survey were analyzed to calculate net displacement (distance from release site). Long-term movement of over 60 km occurred along the windward coast of Oahu (Fig. 3).

The sandy surf zone habitat at the Kahana Bay and Kailua Bay release sites provided good juvenile habitat while rocky high wave energy habitats such as Mokapu Peninsula and Kahuku provided better habitat for larger individuals. The smallest size class released (70-85 mm FL) had the greatest number of days at liberty and the longest range of movement. The smaller movement associated with larger size classes may be owing to their susceptibility to exploitation soon after release.

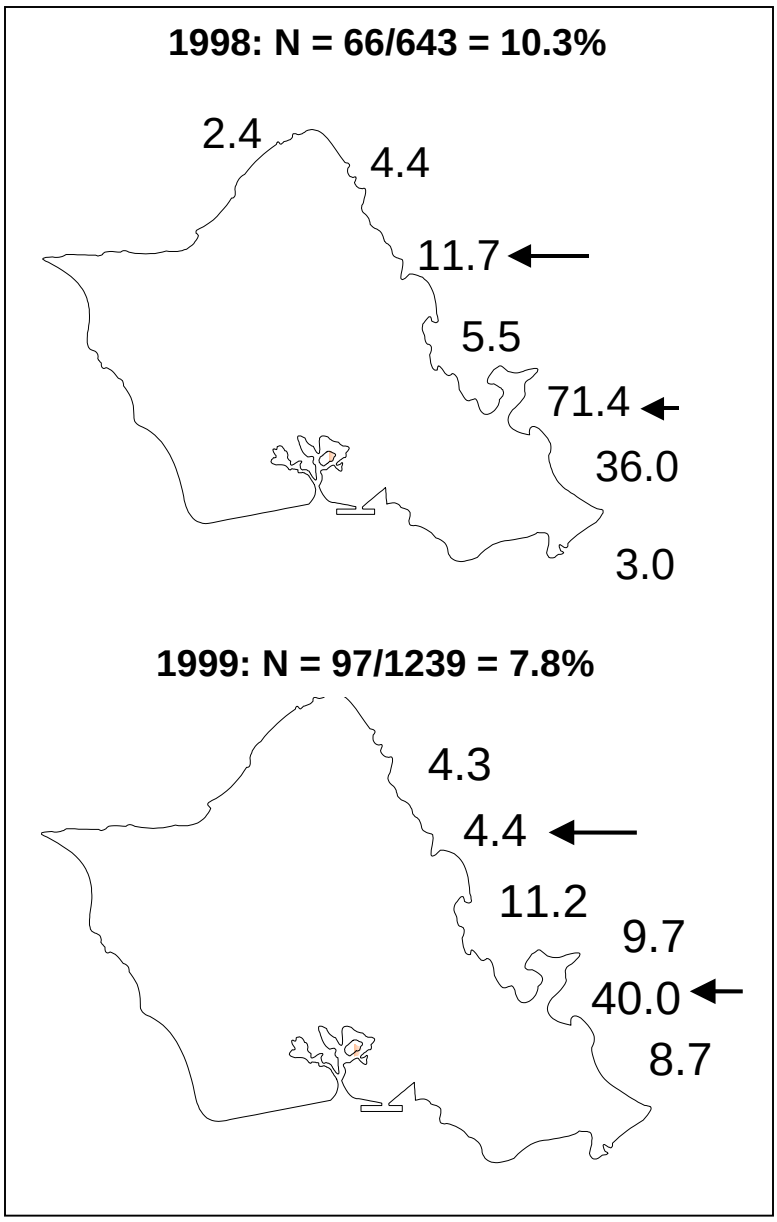

Figure 3. Location of collection and percent contribution of cultured fish released at Kahana Bay in 1997 to the recreational fishery. A: 1998, B: 1999.

Acoustic tracking of small (150-170 mm FL) hatchery - reared moi was conducted periodically over a two-year period (2000-2001). Hatchery fish were surgically implanted with a Vemco acoustic tag, stabilized for two days in a recovery tank, and released with 10-12 similar fish into nursery habitat in Kahana Bay or Kailua Bay. Fish were tracked continuously up to 48 hours after release with an acoustic receiver on a small boat. Position/bearing plots were recorded to estimate day and night habitat range and movement. Acoustic tracking showed limited movement along the sandy surf zone habitat during the day and increased activity at night with more movement offshore. Similar patterns were seen for most of the fish tracked.

Diet and Feeding – Because the diet of an organism has considerable influence upon survival and fitness, the acclimation of hatchery-reared fish to the natural diet is an important component to the success of a release program. Research examined the dietary composition of juvenile, subadult, and adult wild and cultured *P. sexfilis* from the coastal waters of east Oahu, Hawaii (Ogawa *et al.*, in prep). The intention of this study was to establish the major dietary characteristics of wild *P. sexfilis* and to make general dietary comparisons between hatchery-reared and wild *P. sexfilis*. The dietary characteristics of wild and hatchery-reared *P. sexfilis* captured from the east coast of Oahu, Hawaii were very similar. Small benthic crustaceans such as shrimps and amphipods dominated the diet of juvenile fish whereas shrimps, crabs, and fish were the predominant prey items found in adult fish. These prey items are typical among polynemids. Differences in diet were found among size classes for both cultured and wild fish. Horn's overlap index was used to qualitatively compare diets and the Mann-Whitney rank sum test used to detect differences between relative prey weights. Cultured fish feeding habits immediately after release were dissimilar from wild fish, but cultured fish diets rapidly changed to approximate those of wild fish (Fig. 4).

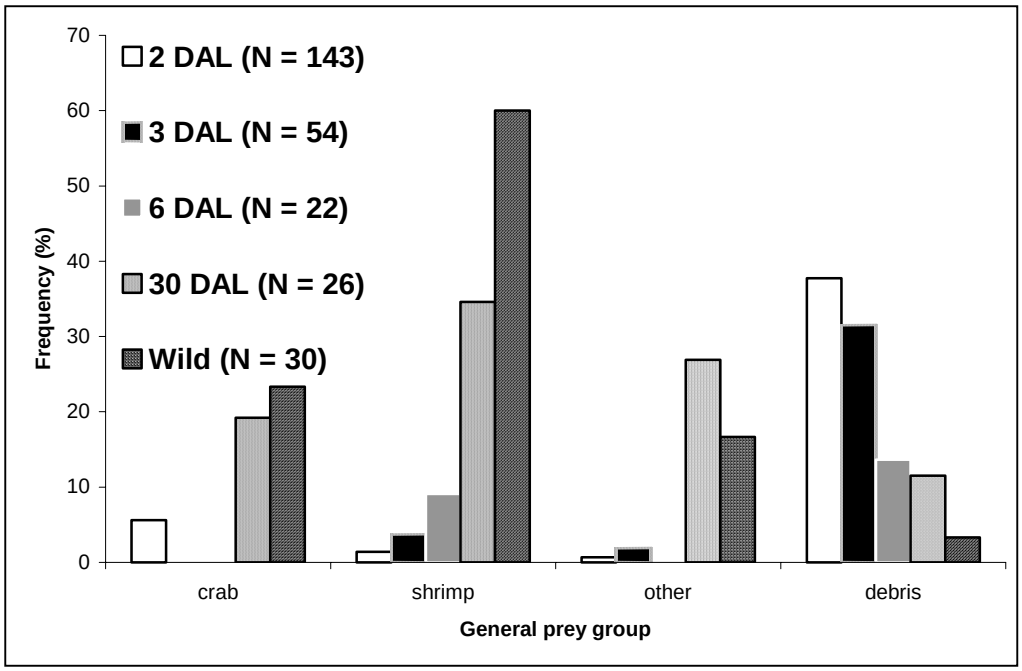

Figure 4. Primary food items found in stomachs of released Pacific threadfin at 2, 3, 6 and 30 days after release, and wild fish, collected in Kahana Bay.

Age and Growth – Increased knowledge of early life history characteristics is needed to address fundamental questions of age and growth patterns of Pacific threadfin, which may be helpful in artificial propagation and larval rearing. The HSM Program conducted a study (Bloom *et al.*, submitted) to validate daily increment formation in otoliths of Pacific threadfin, and to conduct preliminary age determinations on wild juveniles. Wild juvenile Pacific threadfin were collected in Kahana Bay, Oahu, Hawaii, from December 1998 to May 1999. Saggitae were removed, cleaned of endolymph tissue, and stored dry in cell culture trays. Otolith microstructure of wild juveniles was examined. Successful validation of "daily" growth rings was established from cultured

juvenile fish of known age. Age estimations were made for wild juvenile Pacific threadfin (n=50). Growth rates for the initial 30 days of growth are reported for wild juvenile fish, along with changes in daily growth. For wild juveniles collected in 1999, back-calculated hatch days indicated that the year class was the product of multiple spawnings over a four month period in winter.

Behavior and Conditioning

Predation is hypothesized to be a major cause of post-release mortality in stock enhancement projects. We evaluated (Masuda and Ziemann, in press) critical size and release condition of *Polydactylus sexfilis* juveniles in regard to their ability to avoid potential predators such as bluefin trevally *Caranx melampygus* and hammerhead sharks *Sphyrina lewini*. Four different sizes (70, 100, 140 and 190 mm in FL) of threadfin juveniles were released into experimental tanks with predators (5-6 individuals of one of above species) after 24 hrs of acclimatization. Fish were released either gently (control group) or after the stress of 1-min air exposure (stressed group). When they encountered trevallies, fish released at 70 mm or 100 mm were eaten within 7 min 10 sec in maximum, whereas fish released at 140 mm or 190 mm survived for a minimum of 1 hr. There was no difference between stressed and control group. In the case of encountering sharks, there was no size dependent mortality, although individuals in the stressed group tended to be eaten more readily than individuals in the control group. For both predators heavy predation occurred only in the first hour after the release, suggesting that hatchery-reared fish can learn how to avoid predators in a relatively short period. In the practice of stock enhancement we suggest the importance of assessing critical size and species of potential predators before release.

Threadfin are known to spawn near the last quarter of moon phase both in the wild and under culture. Since they utilize the surf zone as their habitat and spawn corresponding to lunar rhythm, we expected that wild threadfin should have activity rhythm corresponding to tidal and lunar rhythm. Cultured threadfin, on the other hand, may or may not have such rhythm, or they may have specific rhythm corresponding to the feeding times in the rearing tanks. The aim of the circadian rhythm experiment (Masuda *et al.*, in press) was to examine the daily and lunar behavioral rhythm of wild and cultured threadfin. Behavior of both wild-caught and cultured fish were video-recorded simultaneously and analyzed. Field sampling and gut content analysis data was also included to extend indoor data to the field. Laboratory experiment suggested that threadfin is a nocturnal species, since both swimming speed and swimming depth was higher at night in both wild and cultured fish. This nocturnal activity may be related to either feeding behavior or migratory behavior. Since they are bottom feeders, off-bottom behavior observed at night may be related to migration rather than feeding. Both field sampling and laboratory experiments suggested that new moon nights would provide better condition for threadfin compared to other moon phases. Therefore it is recommended to release threadfin around new moon to improve the survival potential in the stock enhancement of this species.

Genetic Management

Preliminary aspects of genetic management for Pacific threadfin stock enhancement research at the Oceanic Institute (OI) have been focused on genetic stock identification and broodstock management (Tringali *et al.*, this volume). To investigate genetic structure in threadfin populations potentially impacted by stock enhancement, wild specimens from four locations on Hawaii (n=41) and from three locations on Oahu (n=32) were assayed by sequencing 1045 base pairs of the mitochondrial DNA (mtDNA) control region. Overall, haplotype diversity was high (99.3%); a total of 61 unique haplotypes were observed from the 73 individuals assayed. However, nucleotide diversity was low (0.64%). No phylogeographic structure was evident in clustered haplotypes. Genetic variance was partitioned predominantly among individuals within populations (98%); approximately 1% of the genetic variance occurred between the threadfin from the islands of Oahu and Hawaii. Haplotype distributions did not differ significantly among these two locations. These data, which are preliminary, are suggestive of high gene flow on a regional basis. The female effective population size, estimated using a Maximum Likelihood Metropolis-Hastings sampling method, ranged approximately 200,000-400,000. The sampled population appears to have undergone a large, historical expansion. Taken together, data are consistent with an evolutionarily recent colonization of the species in the Hawaiian Islands. Preliminary studies for broodstock management are focusing on levels of relatedness among female broodstock and female contributions to OI progeny groups. Using mtDNA sequencing, maternity surveys were performed for cultured progeny groups which contained both normal individuals and individuals exhibiting a particular morpho-anatomical deformity. The condition appeared to be manifested ubiquitously and randomly among progeny of the contributing females. Data provided no evidence that inbreeding or maternal effects are causative factors. If controlled by a single autosomal (dominant or recessive) gene, our preliminary results suggest that the condition has very low penetrance/expressivity in the wild threadfin population.

Ecological Basis of Natural Recruitment

Rates of natural recruitment of Pacific threadfin to nursery habitats has been observed to be highly variable between years (Fig. 2). Recruitment success is the result of the actions of a range of factors, both related to the number of larvae produced (size of the reproductive population, spawning frequency and success), and to environmental factors acting at the time of spawning and the early larval stage (low predator abundance, high food availability, favorable physical conditions). Preliminary data collected by the HSM Program suggests a relationship between natural recruitment and environmental factors (Fig 5; Ziemann and Friedlander, in press); in this case, mean annual temperature may be a proxy indicator of overall rainfall, which influences the input of dissolved nutrients into coastal waters.

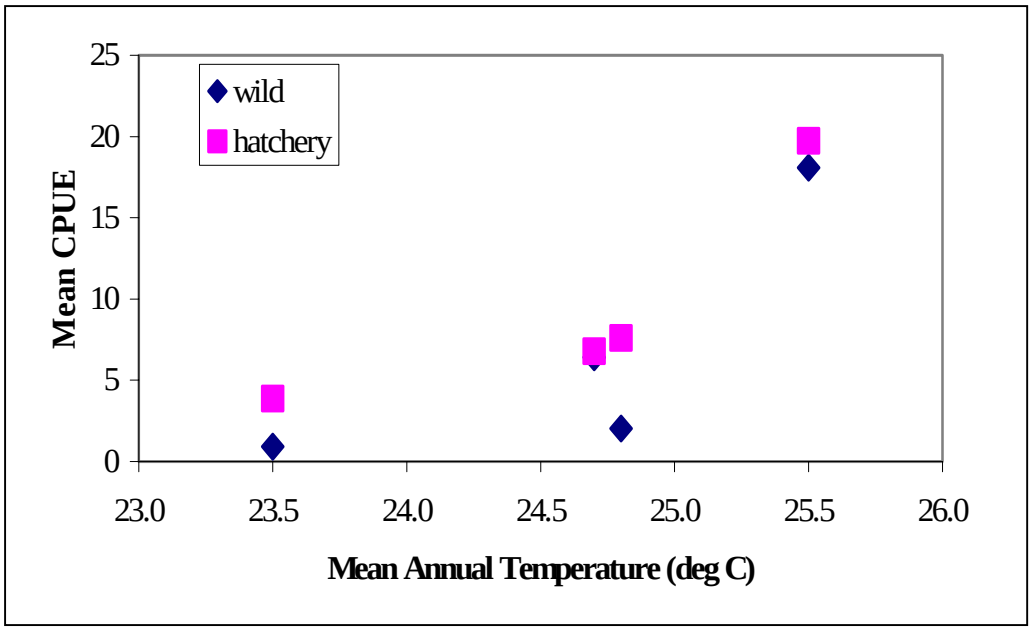

Figure 5. Plot of mean annual catch per unit effort for wild and released year 0 Pacific threadfin along the windward coast of Oahu, related to mean annual water temperature at Kahana Bay, Oahu.

The HSM Program has begun a research component to examine the ecological basis of natural recruitment in Pacific threadfin. The study entails monthly physical, chemical and biological surveys focused on Kahana Bay, a primary site for early threadfin recruitment. Physical oceanographic studies include measurements of currents, and determination of the impacts of tidal exchange on the distribution and concentrations of dissolved nutrients. Nutrient input studies are examining the sources and types of nutrients entering the bay, and generating estimates of uptake and dispersal rates. Biological studies are focusing on the distribution, abundance and major taxonomic components of the benthic and planktonic communities.

Summary

Research into the feasibility of stock enhancement in Hawaii on Pacific threadfin has established the information necessary to design and implement a responsible enhancement program, and has demonstrated the potential contribution released fish can have on localized fisheries. Our research has shown: the optimal release strategy matches natural recruitment patterns; cultured fish adapt quickly to natural conditions; and experimental releases have made significant contributions to Oahu recreational moi fishery. The threadfin population, on the island of Oahu, at least, is severely depleted, suffering from both low adult population size and low and variable recruitment. Research has shown significant interactions between adult population size, natural recruitment, and the impacts of releases. Current research is examining threadfin behavior and conditioning, fisheries demographics and ecology, genetics, the

ecological basis of recruitment success and means to determine the contribution of hatchery-reared fish to reproduction and stock recovery. Major questions on factors affecting population size, nursery carrying capacity and recruitment success, wild *vs.* hatchery fish interactions, and the long-term (multi-generational) effects of releases remain.

Acknowledgments

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